STATISTICAL ASSESSMENT OF THE EFFECT OF A WAVE ENERGY CONVERTER IN FALMOUTH BAY, UK

Joanne K. Garrett[ab], Matthew J. Witt[b], Philippe Blondel[c], Lars Johanning[a]

[a] College of Engineering, Maths and Physical Sciences, University of Exeter, Treliever Rd, Penryn, Cornwall, TR10 9FE, UK
[b] Environment and Sustainable Institute, University of Exeter, Treliever Rd, Penryn, Cornwall, TR10 9FE, UK
[c] Department of Physics, University of Bath, Claverton Down, Bath, BA2 7AY, UK

Joanne K. Garrett, j.k.garrett@exeter.ac.uk

Abstract: *Wave energy has the potential to contribute to the UK's energy mix, producing electricity without producing carbon dioxide. This will have benefits in combatting global climate change, however, the technology may have local negative effects on the environment. A key concern is the potential for underwater noise pollution. Wave energy converters are a novel technology and little is known about the underwater sounds produced.*

A wave energy converter (WEC; BOLT Lifesaver, Fred Olsen Ltd.) was deployed at the Falmouth Bay marine renewable energy test site (FaBTest). The underwater sound levels were recorded at this site for a two-week baseline period, a five-day installation period and intermittent operational and non-operational activity from March 2012 - November 2013 resulting in 14 months of underwater sound recordings.

The wave energy converter sounds are often masked by shipping noise in Falmouth Bay. Previous research suggests the effect of this WEC on underwater sound during power production is minimal [1]. The aim of this paper is to test this using statistical models to quantify the effect of the wave energy converter on underwater sound during installation and operational activity.

Keywords: *Marine renewable energy, underwater noise, wave energy converter,*

1. INTRODUCTION

The UK benefits from a large potential renewable energy resource with the best wind, wave and tidal resources in Europe [2]. Wave and tidal energy are considered necessary if the EU is to meet its renewable energy targets [3] and wave energy has the potential to contribute considerably to the UK's energy mix [4]. In the UK, a variety of wave energy devices have been deployed, or are in the planning stages, in Cornwall [5], Scotland [6] and Wales [7].

The marine environment is under pressure from multiple sources including climate change [8, 9], ocean acidification [10, 11], pollution [12, 13] and overfishing [14, 15]. Therefore, there is a need to develop the marine renewable energy industry as sustainably as possible. Possible negative environmental effects include collision and changes to the benthic and water column environment [16] and a key concern is the potential for underwater noise to affect marine life [17].

Underwater sound was recorded during trialling of a wave energy converter (WEC) in Falmouth Bay, UK. A single passive acoustic monitoring (PAM) device recorded in close proximity (~200 m) to the device over a 17-month period. We compared periods of operational activity with periods of non-operational activity at close points in time.

Initial analyses suggested the effect of this WEC on underwater sound during power production is minimal [1]. On average, there was a negligible difference between the PSD levels between power production during operational activity and periods of inactive status during non-operational activity. However, there was an increased difference within the frequency range of 10 – 100 Hz [1].

Statistical modelling, such as linear regression modelling, is routinely used in the life sciences; but less so in the engineering and acoustics literature. It offers advantages in assessing effects as they are quick to perform and indicate the direction and significance of relationships. Modelling was used in the open source programme R to test statistically whether the WEC had a detectable difference on the underwater sound levels.

2. METHOD

Location

The WEC and PAM devices were deployed at the Falmouth Bay Test Site (FaBTest) on Cornwall’s south coast, UK (Fig. 1), a nursery test site for marine renewable energy devices. It is located within the Port of Falmouth, but outside a Special Area of Conservation [18]. After noise monitoring, a proposed Special Protection Area for wintering seabirds was also designated [19].

Falmouth Harbour and its outer Bay supports a busy commercial port with 1,193 ship arrivals in 2012 [20] and 738 in 2013 [21], of which most visiting vessels are tankers or dry cargo ships. Falmouth Bay is located adjacent to the international shipping lane through the English Channel.

Host ecosystems support a diverse range of marine species including bottlenose dolphins, harbour porpoises [22], basking sharks [23], grey seals and fish along with Annex 1 EU Habitat Directive habitat and species including reef features and Maerl.

The wave conditions at FaBTest range from 2 - 11 s wave period and from 0.1 - 6 m significant wave height (H_s; average of the tallest one-third of the waves) from March 19th 2012 to 5th March 2014.

The WEC

The WEC is a point absorber developed by Fred.Olsen Renewables (Fig. 1). BOLT Lifesaver has three power take off (PTO) units, positioned above the sea surface, which are each moored independently to the seabed, on a ring-shaped hull which has a diameter of 16 m [24]. During the trial at FaBTest, the WEC was inactive and not producing power during high and extreme wave conditions as well as during low wave conditions where it shuts down at wave heights of 0.4 - 0.6 m H_s and below [25]. There were a total of 1,468 production hours and the longest continual power production period was 24 days [25].

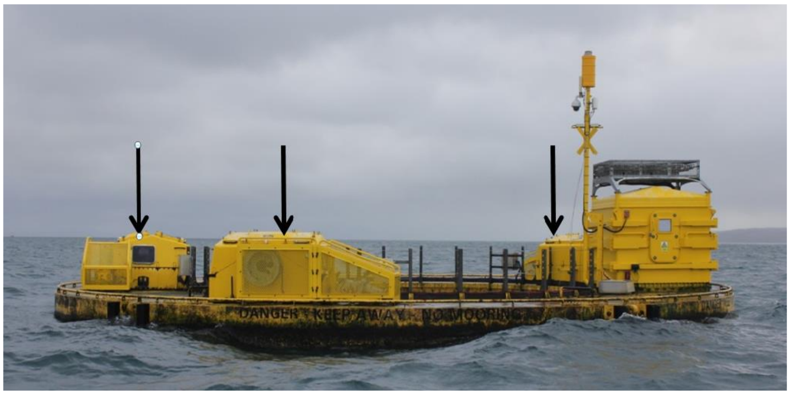

Fig.1: The Fred.Olsen BOLT Lifesaver wave energy converter deployed at FaBTest. The PTOs are marked with downward arrows. Picture credit: 2013 Duncan Paul, Falmouth Harbour Commissioners

Passive acoustic monitoring

Two Autonomous Multichannel Acoustic Recorders (AMA$ G2; Jasco Applied Sciences Ltd.; 24-bit recording using manufacturer-calibrated GeoSpectrumM8E hydrophones) were deployed alternately at the FaBTest. They were programmed to record for the first 30-mins in every hour from June 2012 – November 2013 at a sampling frequency of 64 kHz (effective recording frequency range 10 Hz – 32 kHz). A pistonphone was used (type 42AC; G.R.A.S., Denmark) to test the system's response at 250 Hz, which was a maximum of 1.3 dB different to the expected value by the end of the study. AMARs were deployed using a syntactic foam flotation collar (Jasco Applied Sciences Ltd), with the device floating in the water column ~10–15 m from the seabed at depths ranging from approximately 30 to 45 m. The hydrophone on each AMAR was covered in a cloth shroud (hat). This shroud was used in all but the first deployment (Table 1).

Deployment number	Date of deployment	Position (degrees; WGS84)	Number of days of recording	Number of 30-min files
1	13th June–20th August 2012	N50.098889 W04.995278	68.0	1634
2*	20th August–8th November 2012	N50.100409 W04.996118	81.4	1954
3*	8th November 2012–9th January 2013	N50.100633 W04.995900	62.1	1489
4*	9th January–11th March 2013	N50.101256 W04.996308	61.4	1474
6*	4th June–8th August 2013	N50.100283 W04.997333	77.0	1848
7*	8th August–4th November 2013	N50.100167 W04.998050	98.2	2311

*During deployments 2 to 7, the hydrophone cage was covered with a cloth shroud to reduce flow noise.

Table 1: Deployment history of AMARs in Falmouth Bay.

Acoustic data processing

Custom MATLAB scripts were developed to process the acoustic data (The Mathworks, Massachusetts). A fast Fourier transform (FFT) function was applied to the waveform data, in 1 s segments with a 50% overlap using a Hann window. The hydrophone response curves, provided from the manufacturer’s calibration, were interpolated to provide hydrophone sensitivity value per 1 Hz and used to calibrate the data. A scaling factor of 0.5 was applied which removes the effect of the Hann window on the resulting amplitude [26]. A noise power bandwidth correction of 1.5 was also applied to give the frequency resolution of 1 Hz [26, 27]. The mean of the square pressure values (p_{RMS}) were calculated per minute per Hz and stored. Once all averaging was completed, the square pressure values were converted into decibels (dB) with a reference pressure of 1 µPa.

To calculate third octave levels for each 30-min acoustic recording, the mean minute square pressure values were summed together, within the frequency bands to give a third octave level per band for 1 minute for every half hour file. Third octave bands with the centre frequencies 63 Hz and 125 Hz have been identified as the indicators for the EU’s Marine Strategy Framework Directive (MSFD) under Descriptor 11; energy and noise. The resulting values were then converted to dB, once all processing and averaging was completed. The mean square pressure (p_{RMS}^2), or arithmetic mean, has been used in line with the latest recommendations [28].

Broadband sound pressure levels (SPL_{RMS}) were calculated for overlapping (50%) 1-s segments. These were averaged (median) for each 30-minute sound file before being converted to decibels.

Differences in sound levels were calculated by subtracting a set of mean or median values per 1 Hz from another in decibels to give a difference in sound levels in decibels per 1 Hz.

Tide and wave data

Tidal data (flow rate; metres s^{-1}) for the location of the AMAR deployment were obtained from the POLPRED depth-averaged high- resolution UKCSModel CS20-15HC (horizontal resolution approximately 1.8 km; National Oceanography Centre (UK)).Wave height data were obtained from a Seawatch Mini II directional wave buoy (Fugro 2010) deployed at the FaBTest site, approximately 150 m from the AMAR location. The wave buoy sampled at a frequency of 2 Hz for 1024 s every 30 min. These data were processed using proprietary software (WaveSense, Fugro OCEANOR AS, Norway) to provide a mean significant wave height for each 30-min period [29].

Statistical analyses

30-minute sound files were assigned “Operational” status where at least one PTO was in active status. Where the device was inactive, the status “Non-operational” was assigned. Information regarding status was provided by the device developer. Data were excluded from this analysis where the wave height was <0.5 m as the WEC did not produce power below this height. This resulted in 3,192 datapoints for non-operational status and 1,832 datapoints for operational status.

Linear mixed effects modelling was used in the R environment using the package lme4 [30]. The mixed effects approach facilitates the inclusion of random effects, as well as the fixed effects (the explanatory variables of interest). We include the deployment number as a random effect, to take into account potential differences in deployment characteristics such as location. We modelled the deployments with varying intercepts, or mean values. The mean sound levels varied with season so this was also included as a random effect. The status, wave height and tide speed were included within the model as fixed effects.

The median SPL_{RMS} were tested for autocorrelation and was found to be present. Autocorrelation within variables can increase type I errors, where the null hypothesis is rejected (no relationship) when it is true [31].

Subsets of data were modelled with increasing time intervals. The model residuals (the difference between the predicted and observed values) were checked for autocorrelation. An interval of 4 hours was chosen as this reduced autocorrelation in the residuals while maintaining a sufficient sample size.

RESULTS

Broadband SPL

The median sound level during non-operational activity, for all data points with wave height >0.5 m H_s was 105.1 dB re 1 μPa. The median sound level during operational activity for all data points with wave height >0.5 was louder at 105.3 dB re 1μPa. However, the model results indicate that this increase in sound level was not related to operational activity (Table 2).

Status, wave height and tide speed all had a significant effect on the median broadband sound level. This relationship was positive with wave height and tide speed, where tide speed and wave height increase the sound level also increases. However, the operational status was found to be associated with quieter levels of underwater sound as compared to non-operational status (Table 2).

The median wave height for operational activity was 1.1 m H_s, this is greater than the median wave height during non-operational activity of 0.9 m H_s. This could explain the increased sound level during operational activity as compared to during non-operational activity.

The correlation between the fitted values and the observed values is considered reasonable (Spearman's rank correlation, ρ= 0.58, p<0.001)

Fixed effect	Estimate	Standard error	df	*t* value	*p* value
Status (Operational)	-0.514	0.21	1228.9	-2.41	0.016
Wave height (H_s; m)	0.581	0.17	1343.5	3.34	0.001
Tide speed	3.046	0.56	1341.1	5.40	<0.001

Table 2: Model results for median broadband SPL_{RMS} for operational and non-operational activity.

Third octave levels

The median third octave level with centre frequency of 63 Hz was 79.4 dB during non-operational activity and was louder at 81.0 dB during operational activity. However, the results from the model indicate that the contribution from the wave energy converter is not significant (p is >0.05).

As with the broadband SPL_{RMS}, both the wave height and tide speed had significant positive effects on the 63-Hz band third octave level (Table 3).

The correlation between the fitted values and the observed values was lower than observed for the broadband SPL_{RMS} (Spearman's rank correlation, ρ=0.50, p<0.001).

Fixed effect	Estimate	Standard error	df	*t* value	*p* value
Status (Operational)	0.301	0.39	1347.5	0.767	0.443
Wave height (H_s; m)	4.568	1.09	1344.8	4.187	<0.001
Tide speed	3.370	0.33	1348.0	10.065	<0.001

Table 3: Model results for third octave levels with centre frequency 63 Hz for operational and non-operational activity.

DISCUSSION

The modelling results support the initial analyses which suggested that operational activity of the wave energy converter had overall a minimal effect on the underwater sound levels in Falmouth Bay, UK. Surprisingly, the model results indicate that the median broadband SPL_{RMS} were quieter during operational activity as compared to non-operational activity. The reasons for this are unclear, but could be related to the wave height as the wave energy converter was switched off during the highest waves.

Further work includes testing additional sound parameters and refinement of the modelling method. However, statistical modelling in R represents a useful method to assess the effect of renewable energy on underwater sound.

ACKNOWLEDGEMENTS

This work is funded by the European Social Fund (ESF), the Peninsula Research Institute for Marine Renewable Energy (PRIMaRE; funded by the South West Regional Development Agency), MERiFIC (funded by the European Regional Development Fund through the Interreg IV-A programme), the Technology Strategy Board (TSB), and Fred Olsen Renewables. We are sincerely thankful to David Raymond and David Parish (U. of Exeter) for their technical support.

REFERENCES

[1] **Garrett, J.K.,** *Interdisciplinary study into the effect of a marine renewable energy testing facility on the underwater sound in Falmouth Bay*, in College of Engineering, Mathematics and Physical Sciences, University of Exeter. pp. 370. 2016.

[2] **Department of Energy & Climate Change,** *UK Renewable Energy Roadmap*. London. pp. 106. 2011.

[3] **Badcock-Broe, A., R. Flynn, S. George, R. Gruet, and N. Medic,** *Wave and tidal energy market deployment strategy for Europe*. SI Ocean, 2014.

[4] **Department of Energy & Climate Change.** Wave and tidal energy: part of the UK's energy mix. www.gov.uk. 2013.

[5] **Wave Hub Ltd.** Developers. https://www.wavehub.co.uk/wave-hub-site/developers 2017.

[6] **EMEC**, *Press release: Penguin powers UK grid with wave energy*, 2017.

[7] **Roche, R., et al.,** Research priorities for assessing potential impacts of emerging marine renewable energy technologies: Insights from developments in Wales (UK). *Renewable Energy*, 99, pp. 1327-1341, 2016.

[8] **Polyakov, I.V., V.A. Alexeev, U.S. Bhatt, E.I. Polyakova, and X. Zhang**, North Atlantic warming: patterns of long-term trend and multidecadal variability. *Climate Dynamics*, 34(2-3), pp. 439-457, 2010.

[9] **Rhein, M., et al.,** *Observations: Ocean, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley, Editor, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA. pp. 316. 2013.

[10] **Ciais, P., et al.,** *Carbon and Other Biogeochemical Cycles, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T.F. Stocker, et al., Editors, Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA. pp. 570. 2013.

[11] **Bednarsek, N., R.A. Feely, J.C. Reum, B. Peterson, J. Menkel, S.R. Alin, and B. Hales,** *Limacina helicina* shell dissolution as an indicator of declining habitat suitability

owing to ocean acidification in the California Current Ecosystem. *Proceedings. Biological sciences / The Royal Society*, 281(1785), pp. 20140123, 2014.
[12] **Derraik, J.G.B.,** The pollution of the marine environment by plastic debris: a review. *Marine Pollution Bulletin*, 44(9), pp. 842-852, 2002.
[13] **Law, R.J., et al.,** Contaminants in cetaceans from UK waters: Status as assessed within the Cetacean Strandings Investigation Programme from 1990 to 2008. *Marine Pollution Bulletin*, 64(7), pp. 1485-1494, 2012.
[14] **Jackson, J.B.C., et al.,** Historical Overfishing and the Recent Collapse of Coastal Ecosystems. *Science*, 293(5530), pp. 629-637, 2001.
[15] **Pauly, D., R. Watson, and J. Alder,** Global trends in world fisheries: impacts on marine ecosystems and food security. *Philosophical Transactions of the Royal Society B-Biological Sciences*, 360(1453), pp. 5-12, 2005.
16] **Boehlert, G.W. and A.B. Gill,** Environmental and Ecological Effects of Ocean Renewable Energy Development a Current Synthesis. *Oceanography*, 23(2), pp. 68-81, 2010.
17] **Witt, M., et al.,** Assessing wave energy effects on biodiversity: the Wave Hub experience. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Science*s, 370(1959), pp. 502-529, 2012.
[18] **Joint Nature Conservation Committee**, *Fal and Helford Natura 2000 Data Form*, Natural England, pp. 3, 2011.
[19] **Natural England**, *Natural England Technical Information Note TIN129 Proposals for a Special Protection Area between Falmouth Bay and St Austell Bay*, Natural England, pp. 3, 2014.
[20] **Department for Transport Statistics**, Table PORT0601 ports, ship arrivals by type and deadweight: 2012, www.gov.uk, 2013.
[21] **Department for Transport Statistics**, Table PORT0601 ports, ship arrivals by type and deadweight: 2013, www.gov.uk . 2014.
[22] **Pikesley, S.K., M.J. Witt, T. Hardy, J. Loveridge, J. Loveridge, R. Williams, and B.J. Godley**, Cetacean sightings and strandings: evidence for spatial and temporal trends? *Journal of the Marine Biological Association of the U.K.*, 92(08), pp. 1809-1820, 2011.
[23] **Witt, M.J., et al.,** Basking sharks in the northeast Atlantic: spatio-temporal trends from sightings in UK waters. *Marine Ecology Progress Series*, 459, pp. 121-134, 2012.
[24] **Fred. Olsen Ltd.,** *BOLT Lifesaver System: Hull*. www.boltwavepower.com, 2012.
[25] **Sjolte, J.,** *Marine renewable energy conversion- Grid and off-grid modelling, design and operation*, in Department of Electric Power Engineering, Norwegian University of Science and Technology: Trondheim, Norway. pp. 271. 2014.
[26] **Cerna, M. and A.F. Harvey**, *The fundamentals of FFT-based signal analysis and measurement*. National Instruments, pp. 20, 2000.
[27] **Merchant, N.D., T.R. Barton, P.M. Thompson, E. Pirotta, D.T. Dakin, and J. Dorocicz,** Spectral probability density as a tool for ambient noise analysis. *The Journal of the Acoustical Society of America*, 133(4), pp. EL262-EL267, 2013.
[28] **Van der Graaf, A., et al.,** *European Marine Strategy Framework Directive-Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater noise and other forms of energy*. Brussels: TSG Noise & Milieu Ltd. pp. 75, 2012.
[29] **Ashton, I.G.C., J.B. Saulnier, and G.H. Smith**, Spatial variability of ocean waves, from in-situ measurements. *Ocean Engineering*, 57(0), pp. 83-98, 2013.
[30] **Bates, D., et al.,** *Package 'lme4': Linear Mixed-Effects Models using 'Eigen' and S4 in R Package Version 1.3–13*. pp. 115. 2017.
[31] **Zuur, A.F., E.N. Ieno, and C.S. Elphick,** A protocol for data exploration to avoid common statistical problems. *Methods in Ecology and Evolution*, 1(1), pp. 3-14, 2010.